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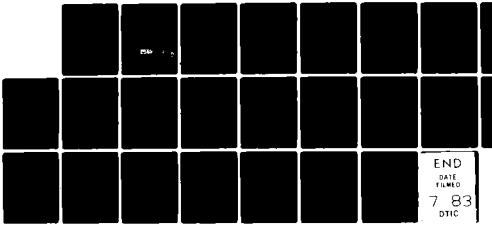

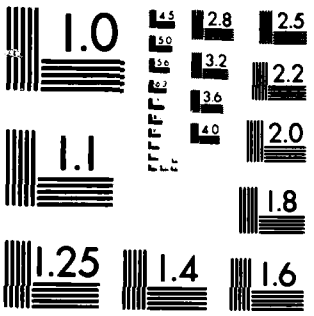

R83-925044-2

RESEARCH PROGRAM ON FACTORS AFFECTING THE BRIGHTNESS OF AC PLASMA PANELS

Final Report

W.L. Nighan and C.M. Ferrar

June, 1983

U.S. Army Research Office
Contract: DAAG29-80-C-0019

UNITED TECHNOLOGIES RESEARCH CENTER
East Hartford, Connecticut 06108

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Under ARO Contract DAAG29-80-C-0019 United Technologies Research Center has conducted a fundamental, theoretical and experimental investigation of the factors affecting brightness, color and efficiency of ac plasma panel displays. Initial emphasis in the program was placed on plasma displays using conventional neon-Penning mixtures. An important finding of this portion of the work was that the brightness and efficiency of such displays are limited

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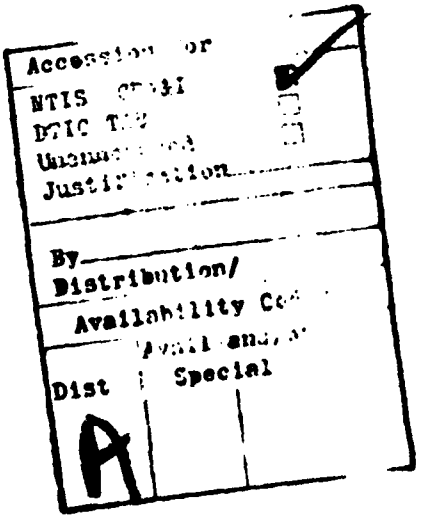
to present levels by several fundamental factors. The possibility of using visible excimer molecule fluorescence for displays was subsequently explored, with attention focused on rare gas-halide and rare gas-oxide excimers. Theoretical analysis indicating that such molecules had promise for the development of bright alternate color displays was confirmed experimentally with the observation of blue fluorescence from Xe_2Cl and green fluorescence from XeO emanating from display discharges. In both cases the measured luminance was found to be greater than that of a neon-Penning mixture excited under the same conditions.



ABSTRACT

Under ARO Contract DAAG29-80-C-0019 United Technologies Research Center has conducted a fundamental theoretical and experimental investigation of the factors affecting brightness, color and efficiency of ac plasma panel displays. During the first phase of the program emphasis was placed on ac plasma displays that use conventional neon-Penning mixtures producing an orange display. An important finding of this portion of the investigation was that the brightness and efficiency of such displays are limited to present levels by several fundamental factors. It was therefore concluded that the most promising way to obtain substantial improvement in plasma display characteristics was to explore the visible emission properties of gas mixtures entirely different from those considered in the past.

Drawing on UTRC's extensive experience in the excimer laser area, the possibility of using excimer molecule fluorescence for plasma displays was explored. Emphasis in this part of the investigation was placed on excimer molecules of the rare gas-halide and rare gas-oxide types which can be produced efficiently under electric discharge conditions. Theoretical analysis indicating that such molecules had promise for development of bright alternate color displays was subsequently verified experimentally with the observation of blue fluorescence from Xe_2Cl and green fluorescence XeO excited in display-type discharges. In both cases the measured luminance was found to be greater than that of neon-Penning mixtures excited under the same conditions. These promising results provided the basis for a new ARO contract (DAAG29-83-C-0013) directed toward evaluation of the practical feasibility of excimer displays. Additionally, UTRC has filed for a U.S. patent covering various aspects of the excimer display concept.

This Final Report, covering the period 4 February 1980 - 4 April 1983, summarizes the key findings of this investigation, and includes as appendices reprints of published papers in which specific results and conclusions of the research are described in detail.

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Research Program on Factors Affecting the Brightness of AC Plasma Panels

TABLE OF CONTENTS

SUMMARY OF KEY RESULTS

Background

There are numerous DoD applications requiring dependable, long-life displays that are compact and rugged, and which consume little power. Typical applications include communication, command and control systems, weapons delivery and control systems, active and passive countermeasures, and cockpit information displays, to name a few. Flat panel displays offer considerable advantage over the CRT for such applications because of their favorable form factor, their reduced weight, size and power requirements, and their potential for improved reliability and flexibility. Although several flat panel technologies have the potential to meet stringent DoD requirements, at present only the neon ac plasma panel, with its intrinsic memory and high resolution, has reached the stage of development required for field implementation in quantity. Additionally, this type of display is well suited for applications requiring large display area; and its transparency permits use as a map overlay.

Conventional plasma display panels of the type presently used in military applications are filled with a neon-Penning gas mixture at a pressure of approximately one-half atmosphere. Although these displays have a number of advantages, they also have certain limitations which restrict their utility, including: brightness which is sometimes insufficient at high ambient light levels, low luminous efficiency (< 1%), and an orange color which is not satisfactory for certain applications. Recognition of these limitations has prompted workers to examine a wide variety of alternate gas mixtures and discharge conditions (Refs. 1 and 2). One promising approach employs UV emitting mixtures of rare gases, sometimes containing an atmospheric species as an additive, in order to excite phosphors to produce one or more visible wavelengths (Refs. 1-3). However, the UV wavelengths (< 200 nm) produced by such mixtures introduce problems associated with phosphor location and display resolution. Recently, direct blue emission has been obtained from mercury-seeded argon excited in an ac plasma panel (Ref. 4). Unfortunately, the blue mercury emission is quite sensitive to temperature variation, a consequence of the strong dependence of mercury vapor concentration on temperature. Thus, to date new techniques for improving the brightness and/or color characteristics of plasma displays have not been fully satisfactory, and only the neon-filled ac plasma panel is presently capable of meeting military requirements.

Neon-Plasma Panel Research

Although the electrical characteristics of neon filled ac plasma panels have been studied extensively and are relatively well understood (Ref. 5), until recently very little was known about the kinetic processes affecting the light-producing $Ne(2p_j)$ states, the group of states representing the second excited electronic configuration in neon. In an effort to devise means to improve the brightness and/or efficiency of neon filled panels, under the present contract UTRC carried out a

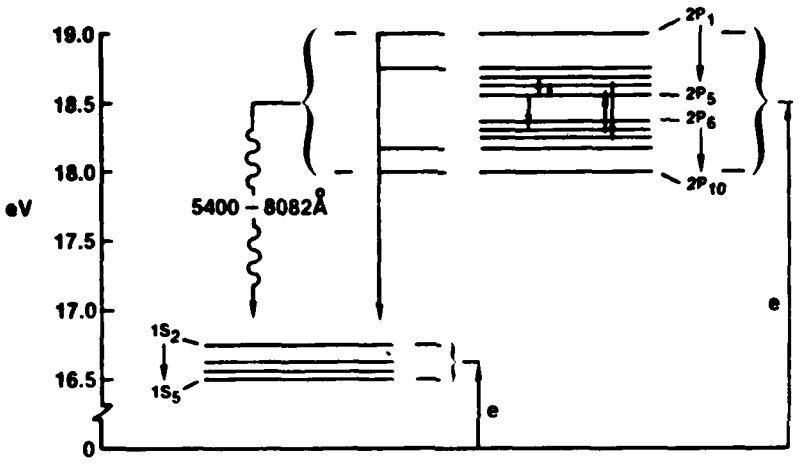

Figure 1. Simplified neon energy level diagram showing the levels of the $1s_j$ and $2p_j$ excited states. Electron impact excitation of ground state neon atoms, collisional mixing of the $2p_j$ levels, collisional relaxation of the $2p_1$, $2p_2$, $2p_9$ and $2p_{10}$ levels to the $1s_j$ manifold, and spontaneous emission from the $2p_j$ levels are indicated (Ref. 6, App. I).

fundamental theoretical and experimental investigation of gaseous electronics phenomena in such devices. Particular emphasis in this study was placed on processes affecting the light-producing neon excited states.

An important result of this work was identification of the factors controlling the production and loss of the ten $Ne(2p_j)$ states which couple radiatively to the four lower lying $Ne(1s_j)$ states (Fig. 1), thus producing the orange emission characteristic of neon-based displays. Quantitative calculations of the time dependent evolution of these states were carried out for conditions representative of ac plasma display operation. Comparison of the computed emission spectra with measured spectra obtained from several panels was found to be very good (Ref. 6), a factor providing important support for the validity of the kinetic modeling procedures used.

The principal findings of this investigation are described in detail in Appendix I, and can be summarized as follows:

- The ten levels of the $Ne(2p_j)$ manifold are excited primarily by electron collisions with ground state neon atoms.
- Collisions with neon atoms mix the $2p_j$ levels, and in addition result in non-radiative deactivation of the $2p_j$ manifold by way of $2p_j$-$1s_j$ transitions.
- Collisional deactivation of the $2p_j$ manifold occurs in a time comparable to the radiative lifetime.
- For conditions typical of plasma panel displays, $2p_j$-$1s_j$ radiative transitions in the 5400-8082 Å wavelength range correspond to a discharge energy utilization efficiency of 1.0-2.0%, with visible radiation accounting for approximately one fourth of this total.
- Of the radiation emitted in the visible region, as much as 35-40% is the result of the $2p_1$-$1s_2$ yellow transition at 5852 Å.

Analysis and interpretation of these results revealed that the low efficiency, and therefore limited brightness, of neon filled panels is fundamental, reflecting the combined effects of several factors, including: a relatively low quantum efficiency ($\sim$ 10%), a $Ne(2p_j)$ discharge excitation efficiency of only 10-20%, significant non-radiative deactivation of the $Ne(2p_j)$ states, and finally, the fact that a substantial amount of the $2p_j$-$1s_j$ radiation falls outside the visible region. In view of these fundamental limitations of the neon-Penning mixture, which is by far the best conventional gas fill, it was concluded that the most promising way to obtain substantial improvement in plasma display characteristics was to explore the visible emission properties of gas mixtures entirely different from those considered previously.

Excimer Display Concept

Drawing on an extensive background and experience in the excimer laser area, the possibility of using excimer molecule fluorescence for displays was explored in detail. A screening of excimer candidates indicated that among the most promising molecules of this type are the rare gas-halides and rare gas oxides. Excimers such as XeF, Kr_2F, Xe_2Cl, and XeO exhibit strong broadband emission in the visible region of the spectrum (Refs. 7-10); and all have been used as sources of visible laser radiation. In addition, XeCl and XeF exhibit very efficient UV flourescence at 308 nm and 351 nm, respectively - wavelengths that may be better suited for excitation of phosphors than the much shorter (< 200 nm) wavelengths typical of the UV emission from rare gases. Thus, it was concluded that if effective excitation of such molecules could be achieved under discharge conditions typical of plasma displays, which are quite different from those of lasers, the emission of one or more of these excimers, either directly or via phosphor excitation, may result in a bright, efficient alternative to the conventional neon-Penning display.

In order to explore this possibility in detail, an analytical model of an excimer display discharge was developed, restricting conditions such as pressure and the temporal variations of voltage and current density to those generally similar to conventional ac plasma panels. Particular attention was focused on the Xe_2Cl and XeO excimers, both of which appear to have promise for use in displays. In connection with the Xe_2Cl studies, mixtures containing 10-20% Xe and a very small amount (< 0.1%) of Cl_2 in neon at a total pressure of 0.5-1.0 atm were examined in detail. For XeO, the mixture studied was 0.5-1.0 atm Xe containing approximately 0.1% O_2. For these conditions, the results of numerical simulation of a typical display discharge were very encouraging, indicating that the fluorescence efficiency and luminious intensity of both the blue Xe_2Cl and green XeO emission would be at least comparable to the orange emission typical of neon-based mixtures.

Guided by these calculations, a preliminary experiment was carried out using an existing ac plasma panel test device filled with an Xe_2Cl mixture as described above. These first tests resulted in bright blue emission identified by spectral analysis as that due to broadband Xe_2Cl fluorescence as shown in Fig. 2; (Ref. 8). Moreover, the apparent brightness of the Xe_2Cl emission was greater than that of a neon-Penning mixture excited in the same device under similar conditions. Subsequently, a small-scale discharge device was constructed to simulate ac plasma panel conditions. When the XeO mixture described above was used in this test device bright green XeO emission was observed (Fig. 3); (Ref. 10). It too was found to exhibit brightness that was greater than that of a neon-Penning mixture excited under similar conditions.

These early results are particularly encouraging and provide impressive initial evidence of the potential for a new and innovative approach to the development of a class of displays based on excimer molecule fluorescence. Appendices II and III contain a detailed discussion of the excimer display concept and the Xe_2Cl and XeO results summarized above.

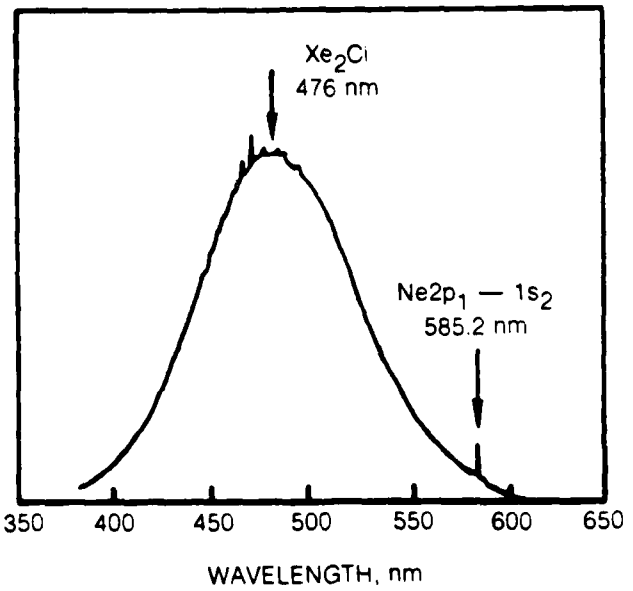

Figure 2. Visible fluorescence spectrum for a Ne-20% Xe-0.1% Cl_2 mixture at a total pressure of 500 Torr excited in an ac plasma panel test device (Ref. 8, App. II).

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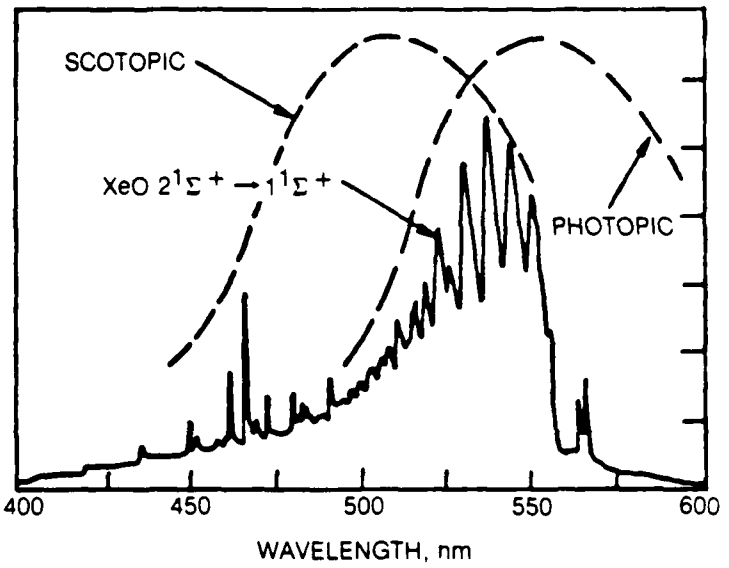

Figure 3. Fluorescence spectrum for a 600T Xe-3TO_2 mixture excited in a discharge test device designed to simulate ac plasma panel conditions. Also shown for comparison are the light adapted (photopic) and dark adapted (scotopic) luminous efficacy curves for the human eye (Ref. 10, App. III)

Future Directions

The results obtained to date represent a proof-of-concept demonstration, and have provided the basis for a UTRC U.S. patent application. However, a demonstration of practical feasibility of the excimer concept requires a considerable amount of additional work. For example, it must be shown that the discharge conditions appropriate for the generation of the high blue/green luminous intensity observed in our initial experiments are compatible with good display resolution, adequate and stable operating voltage margins, acceptable total voltage requirements and, of course, long device life. Of particular interest will be the evaluation of electron-emissive internal panel surface coatings for use with excimer mixtures (e.g., MgO, MgF_2), which have been found to effect significantly most display characteristics. These key issues are presently being addressed under ARO Contract DAAG29-83-C-0013.

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(listed chronologically)

1. W. L. Nighan and W. J. Wiegand: Plasma Kinetic Processes in Neon Gas Discharges. Presented at the Thirty-third Gaseous Electronics Conference, October 6-10, 1980, Norman, OK.

2. W. L. Nighan: Basic Kinetic Processes in Neon Gas Discharge Displays. Presented at the 1980 Biennial Display Research Conference, October 21-23, 1980, Cherry Hill, New Jersey.

3. W. L. Nighan: Basic Kinetic Processes in Neon Gas Discharge Displays. IEEE Transactions on Electron Devices, Vol. ED-28, pp. 625-630, June 1981. (Appendix I)

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W. J. Wiegand

APPENDIX I

BASIC KINETIC PROCESSES IN NEON GAS DISCHARGE DISPLAYS

Basic Kinetic Processes in Neon Gas Discharge Displays

WILLIAM L. NIGHAN

Abstract—Sahni, Lanza, and Howard have carried out a numerical simulation of ac discharges in high pressure neon Penning mixtures for conditions typical of plasma panel displays [1]. Their work has provided valuable insight regarding the electrical characteristics of such devices. However, relatively little is known about the specific factors affecting the radiative properties of neon plasma displays. The present work focuses on this aspect of the problem by analyzing the production and loss processes controlling the populations of the ten levels of the Ne($2p_j$) manifold, which are the primary source of radiation in the visible region of the spectrum. Time integrated radiative intensities of the thirty Ne $2p_j$-$1s_j$ transitions in the 5400–8082-Å range were computed and were found to be in good agreement with measured values obtained using several plasma panel displays.

Introduction

In a recent investigation Sahni, Lanza, and Howard conducted a numerical simulation of ac discharges in high pressure neon Penning mixtures for conditions typical of plasma panel displays [1]. The comprehensive work of these investigators is characterized by its emphasis of fundamental gaseous electronics phenomena occuring in the interelectrode region and by its self-consistent treatment of the physics of the plasma-surface interface. On the basis of their model, Sahni and co-workers were able to predict current-voltage characteristics in good agreement with experimental observations. In addition, their findings have provided valuable insight as regards the fundamental processes which control the electrical/electronic characteristics of plasma panel displays. However, even though such devices are essentially light sources, relatively little is known about the specific factors affecting their radiative characteristics [2]. There are two main reasons for this circumstance: 1) the dynamics of the light producing excited states represent at most a second-order effect, insofar as the electrical properties of neon displays are concerned; and 2) the basic collision rate information required to model the states responsible for the red-orange emission was either unavailable or incomplete until very recently. The required data base has now improved considerably such that a detailed analysis of the radiative characteristics of plasma displays is currently possible. In the present work the numerous production and loss processes which control the populations of the principal neon radiating states are identified, excited state populations and their production efficiencies are computed, and time integrated radiative intensities are calculated and compared with experimental observations. Throughout this investigation, emphasis has been placed on analysis of the discharge conditions typical of plasma panel displays as elucidated in [1].

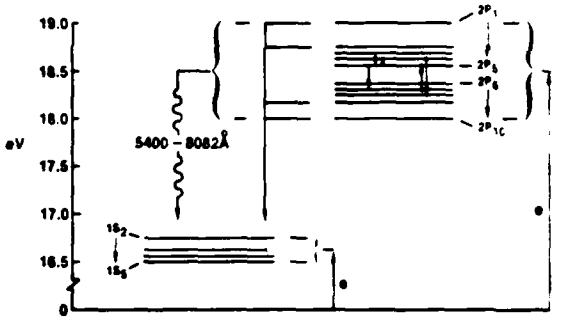

Fig. 1. Simplified neon energy level diagram showing the levels of the $1s_j$ and $2p_j$ excited states. Electron impact excitation of ground state neon atoms, collisional mixing of the $2p_j$ levels, collisional relaxation of the $2p_1$, $2p_2$, $2p_9$, and $2p_{10}$ levels to the $1s_j$ manifold, and spontaneous radiation from the $2p_j$ levels to the $1s_j$ levels are indicated.

Plasma Analysis

Examination of the spectrum typical of neon discharges reveals that the emission in the visible and near IR wavelength regions is dominated by transitions coupling the ten levels of the neon $2p^5 3p$ configuration with the four levels of the $2p^5 3s$ configuration. These $3s$ and $3p$ states represent the first and second excited states of neon, with energy thresholds at 16.6 and 18.3 eV, respectively. The radiating $3p$ states, to be designated[1] hereafter as Ne ($2p_j$), $j = 1 \rightarrow 10$, can be populated by electron collisions with ground state Ne atoms [3] or with atoms in the $3s$ states (Ne ($1s_i$), $j = 2 \rightarrow 5$). Additionally, the Ne($2p_j$) states can be populated by cascade from higher energy states [3]. Subsequent collisions with ground state Ne atoms mix the individual levels of the $2p_j$ and $1s_j$ manifolds, and couple them together as well [4]. The *dominant* processes in this sequence of events are illustrated in Fig. 1. Knowledge of the factors controlling the populations of these excited states,

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[1]Because it is notationally simpler, Paschen notation will be used throughout this paper. Thus the four $1s_j$ levels represent the first excited $3s$ configuration in Ne, while the ten $2p_j$ levels represent the next higher energy $3p$ group.

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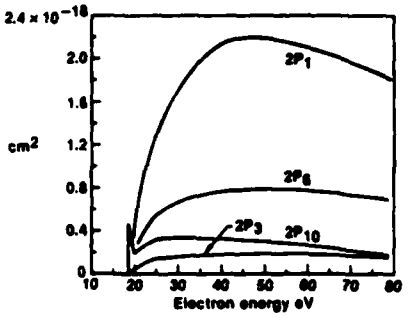

Fig. 2. Cross sections for electron impact excitation of ground state neon atoms to several levels of the $2p_j$ manifold (from [3]).

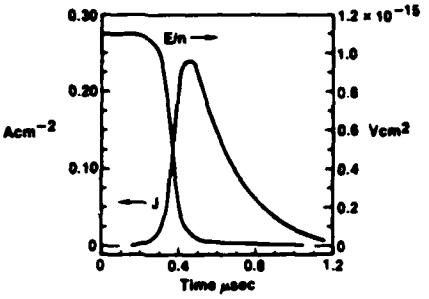

Fig. 3. Illustration of the temporal evolution of E/n and current density for conditions typical of the interelectrode region of plasma panel displays using neon Penning mixtures.

particularly those of the $2p_j$ group, is a prerequisite for understanding the radiative characteristics of neon displays.

Electron-Atom Excitation

Determination of rate coefficients for electron-atom excitation for the nonequilibrium conditions typical of an electric discharge requires knowledge of the electron energy distribution. In plasma panel displays the Penning gas mixture is typically neon at a pressure of approximately 0.5 atm containing about 0.1 percent Xe or Ar as the Penning component [1]. Electron cross sections for elastic collisions, for excitation of the "s" states, and for ionization of the rare gases are generally available [5]. Additionally, Sharpton, St. John, Lin, and Fajen [3] have reported electron cross sections for excitation of the individual levels of the radiating Ne $2p_j$ state, several of which are shown in Fig. 2. The availability of these data permits determination of the electron distribution function by solution of the Boltzmann equation for a specific gas mixture and electric field intensity-neutral particle number density, ratio, i.e., E/n.

E/n Variation

Sahni and co-workers [1] have shown that for conditions typical of plasma panel displays the electric field in the gas evolves in time and undergoes significant spatial distortion caused by the growth of space charge [1]. Thus E/n is time dependent and nonuniform, factors representing a formidable obstacle to analysis. However, the characteristic time for electron energy exchange collisions with neutral particles is very much less than the microsecond time scale typical of the voltage variation. For this reason a time dependent calculation of the electron distribution function is not required, i.e., the energy distribution behaves in a quasi-steady fashion. Moreover, the results of [1] have shown that through much of the 0.01-cm interelectrode gap typical of plasma panels, E/n sweeps from a maximum value of approximately 2.0×10^{-15} V · cm² at a time near discharge ignition, to zero in the fraction of a microsecond during which the discharge current and associated light pulses occur. The temporal evolution of E/n and current density representative of the interelectrode plasma region is illustrated in Fig. 3. Since the primary purpose of the present study is to identify and examine the factors which control the populations of the light producing Ne states, detailed modeling of discharge current-voltage characteristics has not been undertaken. Rather, the plasma medium has been taken to be spatially uniform, having temporal E/n and current density variations typical of those depicted in Fig. 3.

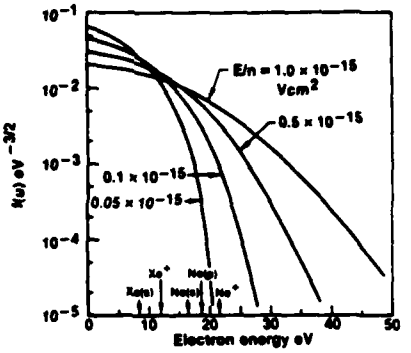

Fig. 4. Dependence of computed electron energy distribution functions on E/n for a Ne-0.1 percent Xe Penning mixture.

Electron Energy Distributions

Presented in Fig. 4 are electron energy distributions determined by numerical solution of the Boltzmann equation for a Ne-0.1 percent Xe Penning mixture and a range of E/n values characteristic of the temporal variation indicated in Fig. 3. Since Maxwellian energy distributions would appear linear in the semilogarithmic plot of Fig. 4, the highly nonequilibrium nature of the computed distribution functions is readily apparent. Nevertheless, the high energy "tail" of the energy distribution, although depleted due to the excitation and ionization processes having the thresholds indicated in the figure, does contain a significant fraction of electrons having energies in excess of the ionization threshold for Ne. Indeed, for this Penning mixture the mean electron energy is approximately 10.0 eV for $E/n = 1.5 \times 10^{-15}$ V · cm², decreasing to a few electron volts as E/n decreases to 1.0×10^{-16} V · cm².

Fractional Energy Transfer

Knowledge of the electron energy distribution permits computation and evaluation of the various individual contributions to electron-neutral energy transfer. This calculation reveals the relative importance of various discharge energy consumption processes, information which is not accessible experimentally. Presented in Fig. 5 are the various fractional contributions to electron neutral energy transfer for the E/n range corresponding to Figs. 3 and 4. This figure indicates

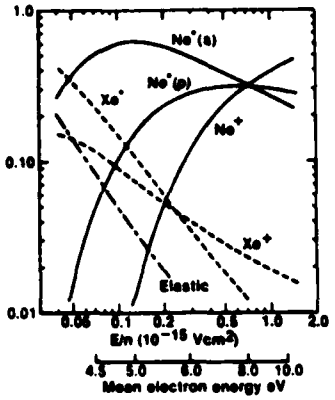

Fig. 5. Computed fractional electron energy transfer as a function of E/n for a Ne-0.1 percent Xe Penning mixture. The corresponding value of mean electron energy also is presented. These results indicate the relative importance of the dominant discharge energy loss processes as explained in the text.

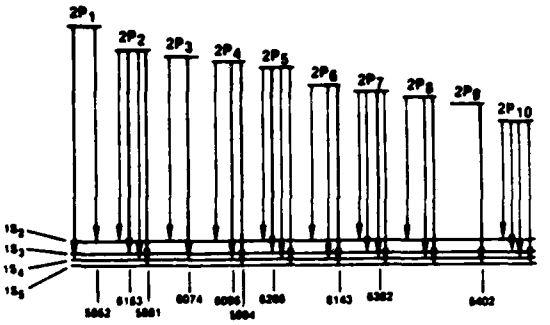

Fig. 6. Illustration of the thirty radiative transitions coupling levels of the $2p_j$ and $1s_j$ manifolds. The dominant transitions in the visible region are indicated.

that in the E/n range corresponding to the peak current density in Fig. 3 (i.e., $E/n \sim 0.05 - 0.2 \times 10^{-15}$ V · cm^2), the dominant electron (i.e., discharge) energy loss process is excitation of the four levels comprising the Ne($1s_j$) manifold, designated Ne*(s) in Fig. 5. Excitation of the collisionally coupled metastable and resonance $1s_j$ states consumes approximately 50-60 percent of the electron energy on average. These neon states subsequently lose their energy by way of Penning ionization of the minority species, Xe in this example. Direct electron impact excitation of the ten levels comprising the Ne($2p_j$) manifold is the dominant production process for the latter, consuming approximately 20 percent of the electron (discharge) energy on average over the E/n range of most importance. Although Fig. 5 shows that electronic excitation of the neon $1s_j$ and $2p_j$ groups of states dominates electron energy transfer, energy loss associated with excitation and ionization of Xe is significant, even though the Xe fractional concentration is only 10^{-3}. This is a reflection of the large Xe cross sections and the fact that Xe excitation and ionization energy thresholds are much lower than those of Ne (see Fig. 4).

Neon-Excited State Processes

Using the E/n dependent rate coefficients computed from the electron energy distributions discussed above, in conjunction with neutral reaction rate data, a self-consistent model of the temporal evolution of the primary Ne excited states has been developed. On the basis of this analysis, the processes which control the populations of the radiating $2p_j$ manifold have been identified. Analysis shows that the ten individual levels comprising the Ne($2p_j$) manifold are excited primarily by electron impact from the ground state of Ne as indicated in Fig. 1. As shown in Fig. 2, the $2p_j$ cross sections exhibit a very large variation from level to level, with the result that $2p_j$ electron excitation rates differ by as much as an order of magnitude.

At pressures of a few hundred torr, intramultiplet mixing of the $2p_j$ levels by collisions with ground state Ne atoms is competitive with the radiative transitions to the $1s_j$ levels [4]. Recently, Chang and Setser [4] have shown that even $2p_j$ collisional deactivation to the $1s_j$ manifold is important, occurring by way of temporary formation of a repulsive Ne_2^* molecular state. These investigators have shown that while intramultiplet collisions mix the radiating $2p_j$ states, intermultiplet collisions connecting the $2p_1$, $2p_2$, $2p_9$, and $2p_{10}$ levels with the $1s_j$ states result in a substantial loss of p state atoms (Fig. 1). For the conditions of the present example, $2p_j$-$1s_j$ collisional deactivation was found to be approximately equal to the radiative loss. Since the quantum efficiency[2] for $2p_j$-$1s_j$ radiative transitions is approximately 10 percent, this collisional loss, when considered along with the ~20 percent of the energy initially fed into the $2p_j$ manifold (Fig. 5), is indicative of a total radiative efficiency of approximately 1 percent for the electrically excited $2p_j$-$1s_j$ transitions.

Fig. 6 and Table I show the thirty specific $2p_j$-$1s_j$ transitions responsible for the observed emission in the 5400-8082-Å range,

TABLE I
NEON $2p_j - 1s_j$ TRANSITIONS

Transition	λ(Å)	Transition	λ(Å)
$2p_1$-$1s_2$	5852	$2p_6$-$1s_2$	6929
-$1s_4$	5400	-$1s_4$	6304
		-$1s_5$	6143
$2p_2$-$1s_2$	6598		
-$1s_3$	6163	$2p_7$-$1s_2$	7024
-$1s_4$	6030	-$1s_3$	6532
-$1s_5$	5881	-$1s_4$	6382
		-$1s_5$	6217
$2p_3$-$1s_2$	6652		
-$1s_4$	6074	$2p_8$-$1s_2$	7173
		-$1s_4$	6506
$2p_4$-$1s_2$	6678	-$1s_5$	6334
-$1s_4$	6096		
-$1s_5$	5944	$2p_9$-$1s_5$	6402
$2p_5$-$1s_2$	6717	$2p_{10}$-$1s_2$	8082
-$1s_3$	6266	-$1s_3$	7438
-$1s_4$	6128	-$1s_4$	7245
-$1s_5$	5975	-$1s_5$	7032

[2]The photon energy corresponding to $2p_j$-$1s_j$ radiative transitions of interest is about 2.0 eV, while the energy required to create a $2p_j$ atom from the ground state is almost 20.0 eV, thus the quantum efficiency is approximately 10 percent.

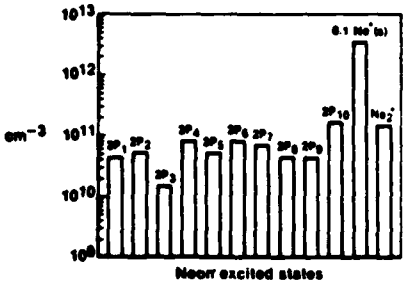

Fig. 7. Computed maximum populations of the $2p_j$ levels for conditions representative of the E/n and current density variations illustrated in Fig. 3. The computed populations of the four $1s_j$ levels and of the Ne molecular states have been summed and are simply indicated $Ne^*(s)$ and Ne_2^*, respectively.

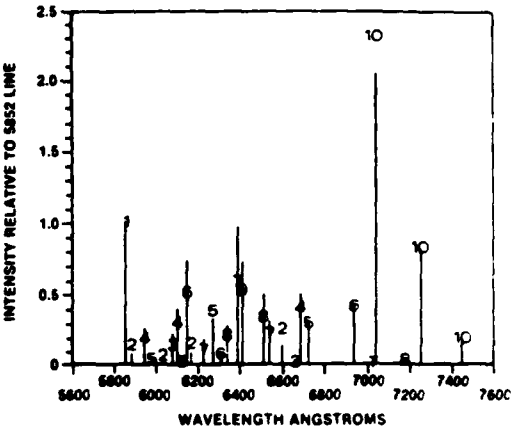

Fig. 8. Computed volumetric time integrated intensities for the $2p_j$-$1s_j$ transitions normalized with respect to the $2p_1 \rightarrow 1s_2$ transition at 5852 A. Computed values are presented as vertical lines in the figure. The numerals shown serve to identify the radiating $2p_j$ state and are positioned so as to represent measured values as discussed in the text. The two weak transitions at 5400 and 8082 A are not shown.

the figure indicating the *major* transitions in the visible region. Note that the initial state for the strong 5852 transition is $2p_1$, the level having by far the largest cross section for formation by electron impact (Fig. 2). Also, Fig. 6 indicates that the strongest visible radiation tends to initiate from those levels in the higher energy half of the $2p_j$ manifold, e.g., $2p_1$-$2p_5$. Thus intramultiplet mixing collisions which tend to drive the $2p_j$ manifold toward equilibrium, for which the lower states are more heavily populated, deplete the states contributing most to output in the visible range.

Computed Ne ($2p_j$) Populations

Presented in Fig. 7 are the values of the populations of the individual Ne ($2p_j$) levels computed for a 350-torr Ne-0.1-percent Xe mixture, and the time-dependent E/n and current density profiles of Fig. 3. The values shown are the peak values corresponding approximately to the E/n value at the peak of the current as indicated in Fig. 3. Although the peak $2p_j$ populations occur near the current density peak, this calculation shows that an effective collisional/radiative lifetime of 10 ns results in a light pulse of somewhat shorter duration than the current pulse (e.g., ~ 0.2 μs). Also shown for comparison is the sum of the populations of the four Ne($1s_j$) levels and the sum of the Ne_2^* molecular states produced from the $1s_4$ and $1s_5$ states by three body collisions. Note that the total $1s_j$ population (which is responsible for Penning ionization of Xe) is approximately one hundred times larger than that corresponding to the sum of the $2p_j$ level populations. The figure also shows that there is about an order of magnitude variation in the populations of the $2p_j$ levels, reflecting variations in the magnitudes of their production cross sections (Fig. 2), and in their total intra- and inter-multiplet quenching coefficients which are significantly different, having values in the $0.5\text{-}5.0 \times 10^{-11}$ $s^{-1} \cdot cm^3$ range [4].

It also is noteworthy that the populations of the $2p_j$ states are influenced by electron impact reexcitation from the alkali atom-like $1s_j$ levels for which the electron cross sections are very large. In the present analysis, this effect was approximated by using the known cross sections for the analogous $3s$-$3p$ transition in sodium [6], weighted by the oscillator strengths of the ns-np transitions in Ne. Multistep excitation of the type described was found to be significant, but of second-order importance for the $2p_j$ levels with the exception of $2p_{10}$. This lowest energy level of the $2p_j$ manifold connects strongly with the highly populated $1s_5$ metastable state (Fig. 6), the importance of which is amplified by the fact that $2p_{10}$ state receives no intramultiplet mixing contribution from below as do the higher lying states of the $2p_j$ manifold, and has a relatively small cross section for excitation from the ground state (Fig. 2). Thus both multistep excitation from $1s_5$ to $2p_{10}$ and cascading from higher $2p_j$ levels make significant contributions to the relatively high population shown in Fig. 7 for the $2p_{10}$ level.

Radiative Characteristics

Based on knowledge of the time-dependent populations of the individual $2p_j$ levels, their radiative lifetimes, and their branching fractions to the $1s_j$ states [4], it is possible to compute the volumetric time integrated energy radiated for each of the thirty transitions in the 5400–8082-Å range. Fig. 8 presents the results of such a calculation normalized with respect to the intensity of the strong $2p_1$-$1s_2$ visible transition at 5852 Å. Also shown in the figure are numerals which serve to identify the radiating p states e.g., the numeral 4 in Fig. 8 appears three times and refers to the $2p_4$-$1s_2$, $2p_4$-$1s_4$, and $2p_4$-$1s_5$ transitions at 6678, 6096, and 5944 Å, respectively. These numbers also are representative of experimental data to be discussed subsequently.

The relatively large intensity of the 5852-Å line is the result of the large electron cross section for excitation of the $2p_1$ level shown in Fig. 2, and essentially unit branching to the $1s_2$ level [4]. In the 6000–6500-Å range, there are several important transitions of approximately the same intensity, a factor reflecting the nearly equal populations (Fig. 7) and radiative lifetimes (~ 19 ns) of the states $2p_2$ and $2p_4$ through $2p_9$, along with mixed branching to the $1s_j$ levels. The large $2p_{10}$ population (Fig. 7) and relatively high branching to the $1s_5$

state is manifest as a very strong transition at 7032 Å, some two-to-three times stronger than the visible 5852-Å line. Overall, for the $2p_j$-$1s_j$ transitions in the 5400–8082-Å range, the present calculations show that the total time integrated radiant energy efficiency relative to the electrical energy deposited in the gas by the discharge was approximately 1.5 percent for the conditions of Fig. 8.

Comparison with Experiment

In order to provide a basis for evaluation of the general validity of the present analysis and interpretation, the spectral intensities of the thirty $2p_j$-$1s_j$ Ne lines emitted by three commercial and experimental plasma display panels were measured using a 0.5-m Jarrell-Ash monochrometer equipped with a Hamamatsu R456 photomultiplier. Measured emissions were referred to an actual power scale through the use of calibration factors determined from the spectral response of the measurement system to radiation from a standard tungsten strip lamp operating at a brightness temperature of 2000°C. The measured relative intensities so obtained were found to be essentially the same for the three panels examined.

The numerals shown in Fig. 8, in addition to identifying the radiating $2p_j$ level, also refer to experimental data points normalized with respect to the measured 5852 intensity. Thus both the computed and measured relative intensities are unity at 5852 Å in Fig. 8. The observed differences between the computed and measured relative intensities are well within a factor of two, and more typically are on the order of ±25 percent. Since such discrepancies are typical of the differences observed among the panels examined experimentally, and of the uncertainties in many of the rate coefficients used in the modeling, the comparison between theory and experiment as exhibited by the data, Fig. 8 is felt to be quite good. The favorable comparison between the computed and measured intensities of the strong lines emanating from the $2p_{10}$ level are felt to be of special significance. Fig. 2 shows that the $2p_{10}$ level has a very small cross section for electron impact relative to the $2p_1$ level, the origin of the 5852-Å line. Analysis shows that the large population of $2p_{10}$ relative to $2p_1$ is a consequence of both intramultiplet cascade downward within the $2p_j$ manifold, and reexcitation of $2p_{10}$ by electron excitation of the metastable $1s_5$ level as discussed previously; both processes weighing about equally for the conditions of Fig. 8. Numerical experimentation indicates considerable sensitivity of the computed $2p_{10}$ population to the treatment of such processes. For this reason the good agreement between computed and measured relative intensity of the radiative energy emanating from this state is felt to be significant insofar as the details of the present analysis and interpretation are concerned.

Emission in the Visible Region

When the computed relative intensities of Fig. 8 are corrected for the response of the eye using a standard photopic correction [7], the familiar [2] pattern of Fig. 9 is obtained. For the conditions of this example, calculations show that approximately 0.5 percent of the total discharge energy is radiated in the visible region, with one third of that figure due to the strong 5852-Å yellow line, a finding which also is found to be in good agreement with experimental observations.

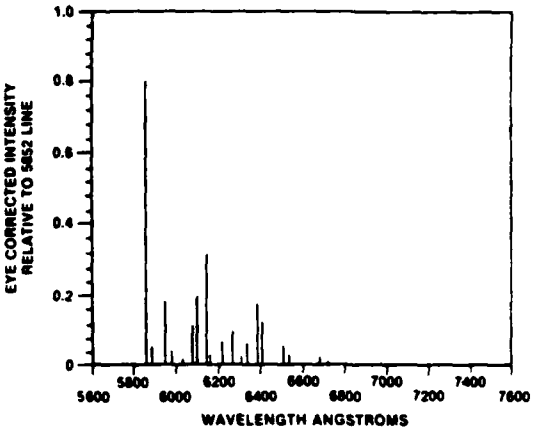

Fig. 9. Computed time integrated intensities of Fig. 8 corrected for the typical response of the eye using the photopic correction of [7].

Conclusions

Using the general electrical characteristics of neon plasma panels as established by the investigations of Sahni, Lanza, and Howard as a basis, this analysis has focused attention on the corresponding radiative characteristics of such devices. The basic factors controlling the production and loss of the radiating Ne($2p_j$) states have been identified, and the time-dependent populations of these states calculated for conditions representative of plasma panel displays. Favorable comparison of computed and measured emission spectra obtained from several plasma panels provides important support for the validity of the present analysis and modeling of the Ne($2p_j$) states.

The principal findings of this investigation can be summarized as follows:

1) The ten levels of the Ne($2p_j$) manifold are excited primarily by electron collisions with ground state neon atoms.
2) Collisions with neon atoms mix the $2p_j$ levels, and in addition result in deactivation of the $2p_j$ manifold by way of $2p_j$-$1s_j$ transitions.
3) Collisional deactivation of the $2p_j$ manifold occurs in a time comparable to the radiative lifetime.
4) For conditions typical of plasma panel displays, $2p_j$-$1s_j$ radiative transitions in the 5400–8082-Å wavelength range correspond to a discharge energy utilization efficiency in the 1.0–2.0 percent range, with visible radiation accounting for approximately one fourth of this total.
5) Of the radiation emitted in the visible range, as much as 35–40 percent is the result of the $2p_1$-$1s_2$ transition at 5852 Å.

Acknowledgment

It is a pleasure to acknowledge the contributions of W. J. Wiegand, who generated the experimental Ne spectral intensity profiles, and of D. W. Setser, who provided Ne($2p_j$) quenching

data prior to publication. Helpful and stimulating conversations with E. Snitzer and R. H. Bullis also are appreciated.

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APPENDIX II

EXCIMER FLUORESCENCE FOR PLASMA DISPLAYS

Excimer fluorescence for plasma displays

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Experimental tests confirm analytical predictions that usefully bright excimer fluorescence in the visible region can be produced under discharge conditions achievable in conventional ac plasma panel configurations. Results are presented for the Xe_2Cl excimer exhibiting broadband blue emission peaked at 476 nm.

PACS numbers: 06.70.Hs, 52.80.Hc, 85.10.Rg, 85.60.Pg

The relatively bright, red-orange emission of the neon glow discharge has led to its use for a variety of display applications. For example, in recent years, intensive development of the neon-Penning ac plasma panel has resulted in reliable, matrix addressable displays with useful memory characteristics.[1] However, comparable performance from devices having emission in the blue and/or green regions of the spectrum has been difficult to achieve. The most promising approaches to the development of alternate color displays have employed UV emitting gas mixtures, with phosphor conversion to visible wavelengths,[1] or direct visible emission from a temperature controlled, mercury-seeded gas mixture.[2] However, both methods suffer from various shortcomings. In this letter we report preliminary analytical and experimental results in support of an alternate approach employing direct visible emission from excimer molecules such as Xe_2Cl.

Among the excimer molecules exhibiting fluorescence in the visible region, certain triatomic rare-gas halides offer particular promise for use in display applications because of their relatively high formation efficiency. These excimers are formed by way of a three-body collision process involving the precursor rare-gas monohalide,[3] e.g.,

$$RGX^* + 2RG \rightarrow RG_2X^* + RG.$$

The rare-gas monohalide RGX^* can be produced very efficiently under discharge conditions upon reactive quenching of rare-gas metastable atoms by certain halogen-containing molecules.[4] For this reason RGX^* excimers have found wide application in electrically excited UV lasers.

Of the triatomic rare-gas halide molecules which fluoresce in the visible, Xe_2Cl appears well suited for displays. In connection with laser applications, experiments using electrically excited, high pressure (5–10 atm) mixtures containing Xe and various chlorine donors have resulted in strong broadband Xe_2Cl emission in the 450–550-nm range.[5] In order to determine whether efficient formation of Xe_2Cl is compatible with the lower pressure and much lower current density conditions characteristic of conventional display devices, detailed modeling of Xe_2Cl kinetic processes was undertaken. Mixtures containing neon as the buffer, 10–20% xenon, and a very small ($\sim$0.1%) amount of Cl_2 at a total pressure of 0.5–1.0 atm were examined. The temporal variations of discharge E/n ratio and current density were restricted to those typical of conventional ac plasma panel devices using neon-xenon Penning mixtures.[6,7] The general features of the analytical and numerical techniques employed are reported elsewhere.[6]

These calculations indicated that for the discharge conditions typical of display devices, Xe_2Cl will be produced by way of the following reaction sequence:

$$e + Xe \rightarrow Xe^* + e,$$

$$Xe^* + Cl_2 \rightarrow XeCl^* + Cl,$$

$$XeCl^* + Xe + RG \rightarrow Xe_2Cl^* + RG,$$

$$Xe_2Cl^* \rightarrow 2Xe + Cl + h\nu, 450\text{–}550 \text{ nm}.$$

For a wide range of discharge conditions the precursor molecule $XeCl^*$ is produced with an energy efficiency in the 10–30% range, a consequence of efficient Xe^* formation by electron impact, followed by rapid reactive quenching of Xe^* by Cl_2 with unit branching[4] to $XeCl^*$. Because of the indicated three-body Xe_2Cl formation process, highly efficient conversion of XeCl to Xe_2Cl is favored at pressures on the order of 10 atm[5]. Nonetheless, the present calculations indicate that even for the subatmospheric conditions typical of display discharges, the Xe_2Cl fluorescence efficiency and brightness should be comparable to or greater than that typical of the conventional neon-xenon Penning mixture.

Experimental tests of the excimer display concept were performed using an ac plasma panel device[1,7] constructed of two plane parallel glass sheets spaced 0.1 mm apart. Orthogonally oriented metal film line electrodes on the opposing interior surfaces were coated with a 0.025-mm glass dielectric, and then with a 200-nm MgO electron emitting layer. Voltage pulses of controllable amplitude, 250-ns duration, and 100-kHz repetition rate were applied to the exposed ends of the electrodes. Capacitive coupling through the glass and MgO coatings produced discharges in the intersheet gap where the opposing 0.08-mm-wide electrodes crossed. Discharge brightness was assessed using a CIE filtered photometer having a response approximating that of the human eye. A scanning monochrometer, with S-5 photomultiplier response, was used to determine spectral content.

A vacuum and gas handling system allowed evacuation and backfill of the plasma panel using various gas mixtures. For these preliminary tests high vacuum techniques, including bakeout, were not employed. Consequently, the charge retention and secondary emission characteristics of the MgO coatings may have been degraded. Multiple purge, evacuate, and fill cycles were used to ensure reasonable gas purity in the panel. Gases were fully mixed in a separate chamber prior to filling the panel. Mixtures were not analyzed after admission to the panel, and so, may have been somewhat altered from their nominal compositions due to imperfect

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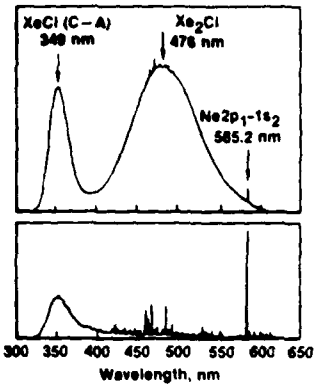

FIG. 1. Discharge fluorescence spectra for a Ne-20% Xe-0.1% Cl_2 mixture excited in an ac plasma panel: upper trace, 500 Torr; lower trace, 75 Torr.

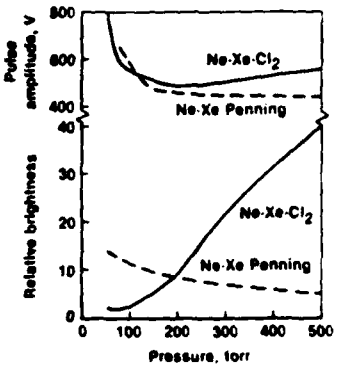

FIG 2 Pressure dependence of excitation pulse amplitude and relative brightness for the Ne-Xe-Cl_2 mixture of Fig 1, and for a Ne-0.1% Xe Penning mixture excited under the same conditions

system passivation for halogen components.

Initial tests were performed using Ne-Xe-Cl_2 mixtures similar to those indicated by analysis as having the most promise. A mixture of Ne-20% Xe-0.1% Cl_2 was found to yield visually bright blue emission under typical panel operating conditions and was selected as a base for more extensive testing.

The emission spectrum for this Ne-Xe-Cl_2 mixture was found to be strongly dependent on total pressure as shown in Fig. 1. At 75 Torr, the spectrum exhibited strong emission from the 585-nm neon line and from the 349-nm XeCl(C→A) band. The 308-nm XeCl(B→X) emission could not be detected due to the transmission characteristics of the glass, but is expected to be very strong for these conditions. Additionally, xenon line radiation is observed which is identifiable with transitions between high lying excited states and the lower $Xe(^1s_j)$ levels. Only a hint of Xe_2Cl emission in the 450–550-nm region is detectable at this pressure. However, at 500 Torr the anticipated Xe_2Cl spectrum is very strong, dominating the visible emission, a result consistent with the three-body Xe_2Cl formation process. For these conditions the discharge was bright blue.

Discharges originating at the electrode crossing points were observed to spread along the electrodes at high excitation voltages, thereby degrading the display resolution capability. Thus, in order to provide a reasonable basis for comparison with the neon-Penning mixture, the maximum usable excitation pulse amplitude was arbitrarily defined as that yielding a discharge spread of 1 mm, about twice the electrode spacing in the experimental device. Figure 2 shows the pressure dependence of this pulse amplitude and of the corresponding relative brightness for the Ne-Xe-Cl_2 mixture discussed above, and for a conventional Ne-Xe Penning mixture under the same conditions. For the experimental conditions employed here, the voltage requirements and discharge brightness of the Ne-Xe-Cl_2 mixture were comparable to those of the Penning mix, especially at the higher pressures. It should be noted, however, that no attempt was made to optimize the operating conditions for either mixture.

The foregoing results indicate the possibility of developing an entirely new class of plasma displays based on visible fluorescence of excimer molecules such as Xe_2Cl. However, further studies of discharge interactions, material compatibilities, operating voltage margins, aging effects, etc., are needed to establish the practical feasibility of such devices. Additionally, other excimers, such as XeF(C→A), which are known to fluoresce strongly in the visible region under appropriate discharge conditions are also being investigated as alternative plasma display emitters.

It is a pleasure to acknowledge numerous helpful discussions with our colleagues E. Snitzer, R. H. Bullis, W. J. Wiegand, and L. A. Newman. This work was supported by the U. S. Army Research Office.

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APPENDIX III

EXCIMER FLUORESCENCE FOR DISPLAY APPLICATIONS

IEEE TRANSACTIONS ON ELECTRON DEVICES VOL. ED-30, NO. 5, MAY 1983

Excimer Fluorescence for Display Applications

CARL M. FERRAR AND WILLIAM L. NIGHAN

Abstract—Over the past decade workers have examined a variety of gas mixtures and phosphor excitation schemes in an effort to develop a viable alternative to the orange neon gas discharge display. To date no approach has been found that offers the combination of brightness, efficiency, and practicality typical of neon-based displays. In this paper we report early results of an investigation directed toward evaluation of excimer molecule fluorescence for display applications. Attention has been focused on rare gas-halide and rare gas-oxide excimers because of their favorable formation kinetics and visible emission characteristics. Modeling of kinetic processes has identified gas mixtures suitable for the generation of visible excimer fluorescence. Experimentation carried out using both a conventional ac plasma panel and a discharge test device has resulted in blue Xe_2Cl emission using Ne-Xe-Cl_2 mixtures, and green XeO emission using Xe-O_2 mixtures. Moreover, the measured luminous intensity of these excimer mixtures was comparable to, and under some conditions greater than, that of neon-Penning mixtures excited under similar conditions. These results indicate the possibility of developing a new class of plasma display based on the visible fluorescence of excimer molecules.

INTRODUCTION

THE RELATIVELY bright orange emission and the favorable electrical characteristics of the neon glow discharge have led to its use for a variety of display applications. For example, in recent years intensive development of the neon-Penning ac plasma panel has resulted in reliable matrix-addressable displays with useful memory characteristics [1], [2]. Although such neon-based displays have a number of advantages, they also have limitations which can restrict their utility for some applications. For example, the luminance is sometimes insufficient at high ambient light levels; the low luminous efficacy (<1 percent) may result in undesirably high power requirements for large-area displays; and the characteristic orange color is not always desirable. Recognition of these limitations has prompted workers to examine a variety of alternate gas mixtures and plasma panel designs.

One approach employs UV-emitting mixtures of rare gases, sometimes containing additives such as N_2, in order to excite phosphors to produce one or more visible wavelengths [3]-[5]. However, problems associated with phosphor location and display resolution are often encountered. Alternate colors and relatively high brightness levels from ac plasma panels have been produced using He containing small amounts of either Xe or atmospheric species, but the luminous efficacy of such mixtures is low [6]. Recently, Sahni [7] reported blue emission from mercury-seeded argon excited in an ac plasma panel; the luminance was found to be substantially higher than that of the standard Ne Penning mixture. However, the strong temperature dependence of the mercury vapor pressure resulted in emission characteristics which were sensitive to temperature variations. Thus it appears that none of these approaches offers a combination of luminance, efficiency and practicality comparable to that of orange neon-based plasma displays.

As a further alternative, we have been exploring the use of excimer[1] molecule fluorescence for display applications [8]. A screening of excimer candidates shows that promising molecules of this type include the rare gas-halides and rare gas-oxides. Excimers such as XeF, Kr_2F, Xe_2Cl, and XeO exhibit strong emission in the visible region of the spectrum; all have been used successfully as sources of visible laser radiation. In addition, XeCl and XeF exhibit very efficient fluorescence and laser oscillation at 308 and 351 nm, respectively—wavelengths that may be better suited for excitation of phosphors than the much shorter wavelengths typical of the UV emission from rare gases. If effective excitation of such molecules can be achieved under discharge conditions typical of plasma displays, which are quite different from those of lasers, the use of one or more of these excimers, either directly or via phosphor excitation, may result in a bright, efficient alternative to the conventional neon-Penning display.

ANALYSIS

A. Rare Gas-Halides

Over the past decade research interest in the physics of excimer molecules has been intense because of their utility in UV/visible lasers [9]. Within this class of molecule, the rare gas-halides have received the most attention because of their unusually high formation efficiency (≳ 10 percent) under electric discharge conditions. Rare gas-monohalides, RGX^* (where X is a halogen), are produced with near unit branching efficiency upon reactive quenching of rare gas metastable atoms by certain halogen molecules [10], [11]. Triatomic

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[1]The term "excimer" is used generally to describe excited molecular species which are not stable in the ground electronic state.

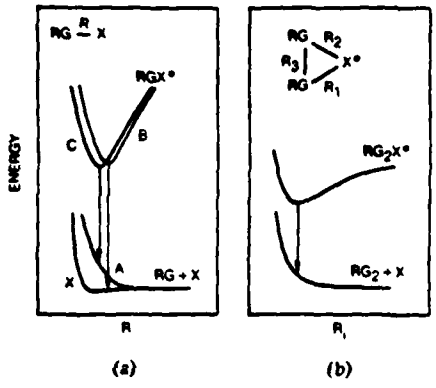

Fig. 1. Potential energy curves for (a) a typical diatomic rare gas-halide RGX^* and (b) for the triatomic, RG_2X^*. The principal transitions giving rise to UV or visible emission are indicated.

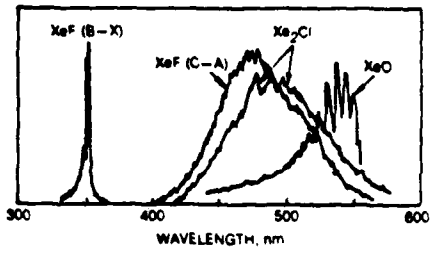

Fig. 2. Typical excimer emission spectra for representative rare gas-halide and rare gas-oxide transitions. (Rare gas-halide emission from Tittel *et al.* [13]).

rare gas-halides can be formed under appropriate conditions by way of a three-body collision process involving the precursor rare gas monohalide [12], e.g.

$$RGX^* + 2RG \rightarrow RG_2X^* + RG. \qquad (1)$$

Schematic potential energy curves for the RGX^* and RG_2X^* excimers are shown in Fig. 1. Due to the weakly bound nature of the X state (Fig. 1(a)), the allowed $B \rightarrow X$ transition of the diatomic molecule is inherently narrow band. However, the $C \rightarrow A$ transition terminates on the highly repulsive A state of RGX, giving rise to a broad bandwidth transition. For the triatomic RG_2X (Fig. 1(b)) the ground state is also repulsive, and thus the emission is characteristically broadband. Depending on the rare gas-halogen combination, the emission wavelengths corresponding to the diatomic and triatomic transitions indicated in Fig. 1 span the 200–600-nm wavelength range [9], [13]. Representative emission spectra for the $B \rightarrow X$ and $C \rightarrow A$ transitions of XeF and Xe_2Cl are presented in Fig. 2.

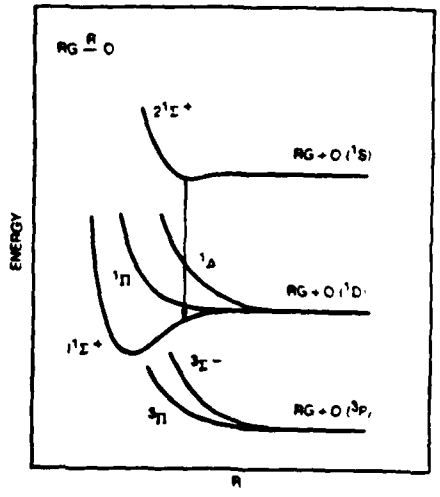

Fig. 3. Potential energy curves for the rare gas-oxide states arising from $RG + O(^3P, ^1D, ^1S)$. The green band $^1\Sigma^+ - ^1\Sigma^+$ transition is indicated

B. Rare Gas-Oxides

The long-lived (~1 s) $O(^1S)$ atom, produced by dissociative excitation of O_2 or by excitation of ground state oxygen atoms, is known to form transient radiating molecular species with the rare-gases [14], [15], i.e.

$$O(^1S) + 2RG \rightarrow RGO^* + RG. \qquad (2)$$

The transition probability of the rare gas-oxide excimer so formed is five-to-six orders of magnitude larger than that of the oxygen $^1S \rightarrow ^1D$ green auroral transition [14]–[16]. Thus in certain rare gas-oxygen mixtures, this collisional-radiative process results in a broadened and slightly shifted $O(^1S)$ emission which is greatly enhanced in intensity. The schematic potential energy curves for the RGO states [16] of importance are shown in Fig. 3, which illustrates the $^1\Sigma^+ - ^1\Sigma^+$ green band transition and also shows the very weak (<0.1 eV) bonding of the radiating $2^1\Sigma^+$ RGO state.

Of the rare gas-oxides the $2^1\Sigma^+$ state of XeO has the largest bond energy and transition probability, factors contributing to the generation of intense green band emission from certain Xe-O_2 mixtures. Additionally, Fig. 2 shows that the XeO $2^1\Sigma^+ \rightarrow 1^1\Sigma^+$ emission spectrum reaches its peak intensity near 540 nm and is therefore very well matched to the response of the eye.

C. Discharge Modeling

Because the triatomic rare gas-halides and the rare gas-oxides are produced in three-body collisions ((1) and (2)), their forma-

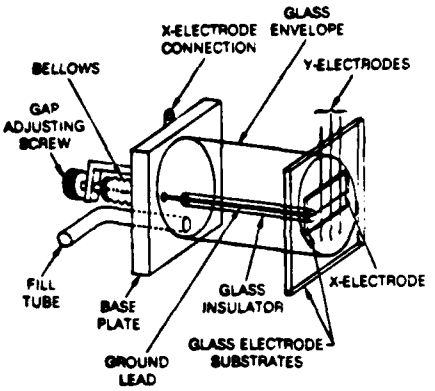

Fig. 4. Illustration of the discharge test device used to simulate conditions typical of ac plasma panels.

tion is favored at high pressures. Indeed, in laser applications typical operating pressures reach several atmospheres [13]. Additionally, the excitation current densities in electrically excited lasers must be very high to ensure the development of adequate net gain. In order to determine whether efficient formation of the excimer molecules discussed above is compatible with the substantially lower pressures and current densities characteristic of conventional display devices, detailed modeling of excimer kinetic processes was undertaken. Particular attention in this study was focused on Xe_2Cl and XeO, both of which appear to have promise for use in displays. Following the procedures reported previously [8], [17], the pressure and the temporal variations of discharge voltage and of current density were restricted to those typical of conventional ac plasma panel devices [17], [18]. In connection with the Xe_2Cl studies, mixtures containing 10-20 percent Xe and a very small amount (~0.1 percent) of Cl_2 in neon at a total pressure 0.5-1.0 atm were examined. For XeO, the mixture studied was 0.5-1.0 atm Xe containing approximately 0.1 percent O_2. For these conditions the results of numerical simulation of an excimer ac plasma panel display were very encouraging, indicating that for both Xe_2Cl and XeO, fluorescence efficiency and luminous intensity comparable to those typical of neon based mixtures should be attainable.

Experimental Results

A. Apparatus

Experimental tests of excimer display feasibility were performed using both a conventional ac plasma panel device described previously [8] and the simple discharge test device illustrated in Fig. 4. The discharge region of the test device is similar in configuration to a conventional plasma panel; but provisions have been made for adjustment of the interelectrode discharge gap, and for convenient device disassembly. These features simplify tube modifications and allow access to

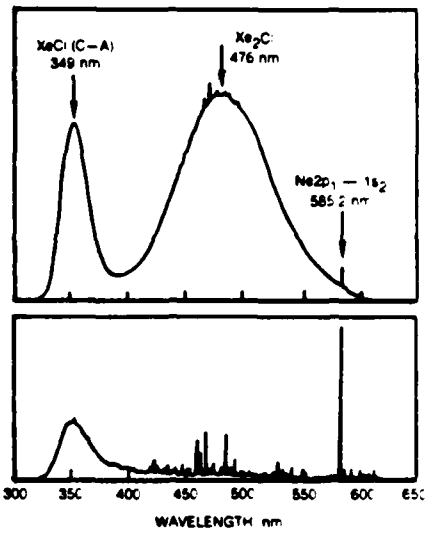

Fig. 5. Fluorescence spectrum for a Ne-20 percent Xe-0.1 percent Cl_2 mixture excited in an ac plasma panel: upper trace, 500 torr; lower trace, 75 torr.

internal components for evaluation of surface changes or for application of special surface treatments. The variable gap is useful in optimizing discharge characteristics when mixture conditions are changed. In addition, the gap can be opened when the tube is evacuated and refilled to speed the otherwise sluggish gas flow in the interelectrode region. The volume-to-surface ratio of the test device is large compared to that of a plasma panel, making it less sensitive to gas composition changes that may occur as the result of plasma-surface interactions. A versatile gas handling system permits rapid, accurate mixing of gases.

Emission brightness was determined using a CIE filtered photometer having a response approximating that of the eye, and a scanning monochromator was used to determine spectral content. Use of fast photomultiplier electronics permitted time resolved optical emission measurements. Rectangular pulses of variable amplitude, pulsewidth and repetition rate were used to drive the test panel and discharge test device.

B. Xe_2Cl Emission

Initial tests were performed using the plasma panel filled with Ne-Xe-Cl_2 mixtures indicated by analysis as having the most promise [8]. A mixture of Ne-20 percent Xe-0.1 percent Cl_2, for example, was confirmed to yield bright blue emission under typical operating conditions. The emission spectrum for this mixture was found to be strongly dependent on total pressure as indicated by the data shown in Fig. 5. At 75 torr, the spectrum exhibited strong emission from the 585-nm neon line and from the 349-nm XeCl ($C \rightarrow A$) band. The 308-nm XeCl ($B \rightarrow X$) emission could not be detected due

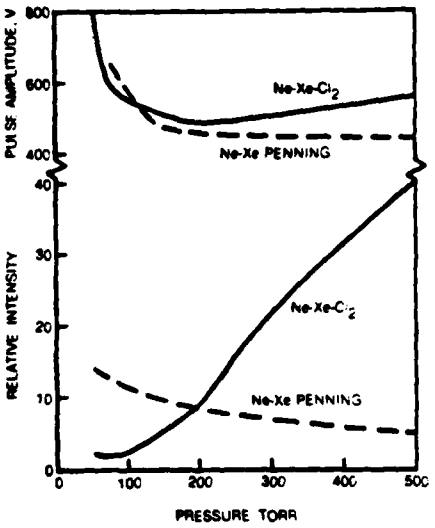

Fig. 6. Pressure dependence of the excitation pulse amplitude (see text) and luminous intensity for the Ne-Xe-Cl_2 mixture of Fig. 5, and for a Ne-0.1 percent Xe Penning mixture.

to the transmission characteristics of the glass, but was expected to be very strong for these conditions. Additionally, xenon line radiation was observed which was identifiable with transitions between high lying excited states and the lower $Xe(^1s_j)$ levels. Only a hint of Xe_2Cl emission in the 400-600-nm region was detectable at this pressure. However, at 500 torr the blue Xe_2Cl emission was strong, dominating the visible fluorescence. This result is consistent with the three-body Xe_2Cl formation process. For these conditions, modeling indicated that the Xe_2Cl excimer was produced by way of the following reaction sequence:

$$e + Xe \rightarrow Xe^* + e$$

$$Xe^* + Cl_2 \rightarrow XeCl^* + Cl$$

$$XeCl^* + Xe + RG \rightarrow Xe_2Cl^* + RG$$

$$Xe_2Cl^* \rightarrow 2Xe + Cl + h\nu, \quad 400\text{-}600\ \text{nm}. \qquad (3)$$

For the conditions of Fig. 5 discharges originating at the electrode crossing points were observed to spread along the electrodes at high excitation voltages, thereby degrading the display resolution capability. Thus in order to provide a reasonable basis for comparison with a neon-Penning mixture, the maximum usable excitation pulse amplitude was arbitrarily defined as that yielding a discharge spread of 1 mm, about twice the electrode spacing in the experimental panel. Fig. 6 shows the pressure dependence of this voltage plus amplitude and of the corresponding relative luminous intensity for the Ne-Xe-Cl_2 mixture discussed above, and for a conventional Ne-Xe Penning mixture under the same conditions. This figure shows that the relative emission intensity of the Ne-Xe-Cl_2 mixture became substantially greater than

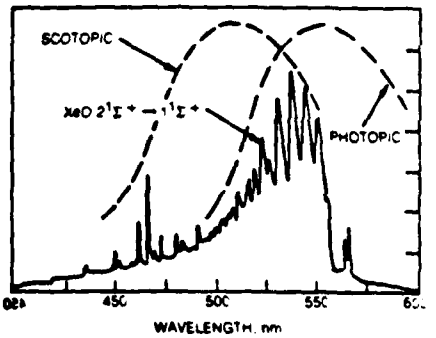

Fig. 7. Fluorescence spectrum obtained using 600 torr Xe and 0.3 torr O_2 in the discharge device of Fig. 4. Also shown for comparison are the light adapted (photopic) and dark adapted (scotopic) luminous sensitivity curves for the human eye.

that of the Ne Penning mixture as the pressure was increased above 250 torr. The voltage requirements were comparable for the two mixtures even though the charged particle production and loss processes differ significantly. It should be noted that exposure to Cl_2 probably degraded the secondary electron emission characteristics of the interior MgO overcoat material [8], [18] of the panel, requiring increased operating voltages. Indeed, Fig. 6 shows that the measured voltages for *both* the Ne-Xe-Cl_2 mixture and the Penning mixture exceeded those typical of conventional panels with aged MgO surfaces by more than a factor-of-two.

C. XeO Emission

Evaluation of XeO as an excimer candidate for displays was carried out using the discharge test device shown in Fig. 4. Xenon at pressures in the 0.5-1.0 atm range containing a few tenths of a torr O_2 (~0.1 percent) was found to yield bright green XeO emission. The measured green band XeO emission spectrum is presented in Fig. 7. For this mixture discharge modeling indicated that the kinetic chain resulting in XeO $2^1\Sigma^+ \rightarrow 1^1\Sigma^+$ emission was as follows:

$$e + Xe \rightarrow Xe^* + e$$

$$Xe^* + O_2 \rightarrow O(^3P) + O(^3P) + Xe$$

$$\rightarrow O(^3P) + O(^1S) + Xe$$

$$Xe^* + O(^3P) \rightarrow O(^1S) + Xe$$

$$O(^1S) + 2Xe \rightleftarrows XeO(2^1\Sigma^+) + Xe$$

$$XeO(2^1\Sigma^+) \rightarrow XeO(1^1\Sigma^+) + h\nu, \quad 450\text{-}575\ \text{nm}. \qquad (4)$$

Analysis shows that the kinetic chain resulting in XeO formation is less efficient than that typical of the rare gas-halide excimers, primarily because quenching of rare gas excited states by O_2 results in relatively little $O(^1S)$ formation [19]. However, there is some practical advantage to using O_2 instead of the more reactive halogens. Moreover, Fig. 7 shows that the

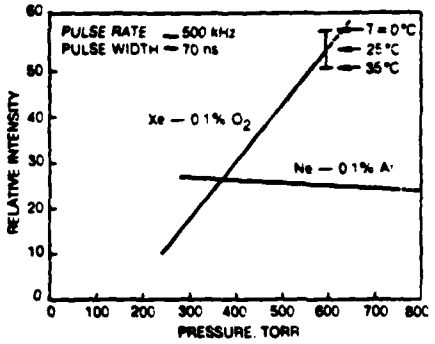

Fig. 8. Pressure dependence of the luminous intensity for a Xe-0.1 percent O_2 mixture and for a Ne-0.1 percent Ar Penning mixture.

XeO emission is very well matched to the sensitivity of the eye, a factor which compensates for inefficiency in the XeO production sequence.

The luminous intensities measured for the Xe-O_2 mixture discussed above are compared in Fig. 8 with those for a Ne-Ar Penning mixture excited in the same discharge device. For these tests the discharge gap was set at about 0.1 mm and the insulating surfaces terminating the discharges were of uncoated potash soda glass approximately 0.1 mm thick. The excitation pulse amplitude was centered in the margin observed between discharge ignition and extinction voltages. Operating voltages for Xe-O_2 mixtures typically exceeded those for Ne-Ar Penning mixtures by 50 to 100 percent. At high pressures, shown by dotted lines in Fig. 8, the voltage margin became too small to measure reliably.

Fig. 8 shows that the intensity of the Ne Penning mixture was relatively insensitive to pressure in the discharge test device, a trend also observed using the plasma panel (Fig. 6). However, the green emission from the Xe-O_2 mixture increased rapidly with increasing pressure, reflecting the kinetics of the XeO($2^1\Sigma^+$) formation process (4). For pressures above 400 torr the luminous intensity of the XeO emission substantially exceeded that of the Ne-Ar Penning mixtures.

The weak XeO($2^1\Sigma^+$) bonding indicated in Fig. 3 suggests that the green band $^1\Sigma^+ - {}^1\Sigma^+$ emission intensity may be sensitive to temperature variations. Preliminary data showing the temperature sensitivity of XeO emission at a pressure of 600 torr is included in Fig. 8. Although the temperature control and measurement for these tests were rather crude, the observed dependence of the green band emission intensity was not strong, in accord with expectations based on the XeO($2^1\Sigma^+$)-O(^{1}S) equilibrium coefficient [15].

Discussion and Conclusions

The foregoing results indicate the possibility of developing a new class of plasma display based on the fluorescence of excimer molecules. Results to date show that electric discharges similar to those of conventional neon based ac plasma panels can be used for the generation of efficient emission in the blue and green spectral regions from excimers such as Xe_2Cl and XeO. Analysis also suggests that other excimer transitions such as XeF($C \rightarrow A$) may have promise.

Excimer molecule formation is favored at pressures higher than those typical of neon based devices. Additionally, charged particle and excited atom loss rates tend to be increased by the presence of halogens and/or oxygen in the excimer mixtures. For these and related reasons optimum excimer emission in the tests conducted to date required voltages higher by 30 to 100 percent and drive frequencies higher by factors of two to twenty than those typical of neon-Penning mixtures. However, for such conditions the observed luminous efficacy and intensities of both the green XeO and blue Xe_2Cl emission were comparable to, and in some cases substantially greater than, those of the orange emission from neon-Penning mixtures.

Demonstration of the practical feasibility of excimer based displays requires further work. For example, it must be shown that discharge conditions appropriate to production of the high blue/green luminous intensity observed to date are also compatible with: good display resolution, adequate and stable operating voltage margins, acceptable total voltage requirements, and long device life. Future efforts will be directed toward resolution of these issues.

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